Measurements of time-dependent CP violation in $B^0 \to \omega K_S^0$, $f_0(980)K_S^0$, $K_S^0\pi^0$ and $K^+K^-K_S^0$ decays

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Abstract

We present measurements of time-dependent CP asymmetries in $B^0 \to \omega K_S^0$, $f_0(980)K_S^0$, $K_S^0\pi^0$ and $K^+K^-K_S^0$ based on a sample of 535 $\times 10^6$ $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB energy-asymmetric e^+e^- collider. One neutral B meson is fully reconstructed in one of the specified decay channels, and the flavor of the accompanying B meson is identified from its decay products. CP-violation parameters for each of the decay modes are obtained from the asymmetries in the distributions of the proper-time intervals between the two B decays.

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The Standard Model (SM) decribes CP violation in B^0 meson decays using the complex phase of the 3×3 Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix [1]. CP asymmetries in neutral B meson decays into CP eigenstates f exhibit a time-dependent behavior

$$A(\Delta t) = \mathcal{S}_f \sin(\Delta m_d \Delta t) + \mathcal{A}_f \cos(\Delta m_d \Delta t) \tag{1}$$

where $\mathcal{S}_f$ and $\mathcal{A}_f$ are the CP violation parameters, Δm_d the mass difference between the two B^0 mass eigenstates, Δt the difference between the decay time of the signal B^0 ($\overline{B}^0$) and of the opposite-side $\overline{B}^0$ (B^0). The SM predicts that for most of the decays that proceed via the quark transitions $b \to s\overline{q}q$ ($q = u, d, s$) the relations $\mathcal{S}_f = -\xi_f \sin 2\phi_1$ and $\mathcal{A}_f \simeq 0$, where $\xi_f = +1(-1)$ corresponds to CP-even (-odd) final states, hold to a good approximation [2]. With physics beyond the SM, these decays may receive significant contributions that depend on a phase that is different from the SM prediction. A comparison of the effective $\sin 2\phi_1$ values, $\sin 2\phi_1^{eff}$, with $\sin 2\phi_1$ obtained from the decays governed by the $b \to c\overline{c}s$ transition is thus an important test of the SM.

Among the final states studied, ωK_S^0 and $K_S^0\pi^0$ are CP-odd modes, $f_0(980)K_S^0$ is a CP-even mode, while $K^+K^-K_S^0$ is a mixture of both $\xi_f = -1$ and $+1$. The SM expectation for this latter mode is $\mathcal{S}_f = -(2f_+ - 1)\sin 2\phi_1$, where f_+ is the CP-even fraction. A measurement of f_+ was obtained using isospin relation [6] with a 357 fb^{-1} data sample and gives $f_+ = 0.93 \pm 0.09(\text{stat}) \pm 0.05(\text{syst})$.

Recently, it was found that the direct CP asymmetries in $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ differ significantly [3] while they were naively expected to be same [4]. Using the $B^0 \to K_S\pi^0$ result, an additional test to understand the situation can be made by comparing the measured $\mathcal{A}_f$ value and the value predicted by a sum rule [5] using asymmetry measurements from the other $B \to K\pi$ decays.

Previous measurements of CP asymmetries in $b \to s\overline{q}q$ transitions have been reported by Belle [7] and BaBar [8]. Belle's previously published results of CP in $B^0 \to \omega K_S^0$, $f_0(980)K_S^0$, $K_S^0\pi^0$ and $K^+K^-K_S^0$ were based on a 253 fb^{-1} data sample corresponding to 275×10^6 $B\overline{B}$ pairs. In this report, we describe improved measurements incorporating an additional 239 fb^{-1} data sample for a total of 492 fb^{-1} (535×10^6 $B\overline{B}$ pairs).

At the KEKB energy-asymmetric e^+e^- (3.5 on 8.0 GeV) collider, the $\Upsilon(4S)$ is produced with a Lorentz boost of $\beta\gamma = 0.425$ nearly along the electron beamline (z). Since the B^0 and $\overline{B}^0$ are approximatively at rest in the $\Upsilon(4S)$ center-of-mass system (cms), Δt can be determined from the displacement in z between the two decay vertices: $\Delta t \equiv \Delta z/(\beta\gamma c)$.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere [10]. Two different inner detector configurations were used. For the first sample of 152 $\times 10^6$ $B\overline{B}$ pairs, a 2.0 cm radius beampipe and a 3-layer silicon vertex detector were used; for the latter 383 $\times 10^6$ $B\overline{B}$ pairs, a 1.5 cm radius beampipe, a 4-layer silicon detector and a small-cell inner drift chamber were used [11].

We reconstruct the following B^0 decay modes to measure CP asymmetries: $B^0 \to \omega K_S^0$, $f_0(980)K_S^0$, $K_S^0\pi^0$ and $K^+K^-K_S^0$. We exclude K^+K^- pairs that are consistent with a $\phi \to K^+K^-$ decay from the $K^+K^-K_S^0$ sample. The intermediate meson states are reconstructed

from the following decays: $\pi^0 \to \gamma\gamma$, $K_S^0 \to \pi^+\pi^-$, $\omega \to \pi^+\pi^-\pi^0$ and $f_0(980) \to \pi^+\pi^-$. Charged tracks reconstructed with the CDC, except for tracks from $K_S^0 \to \pi^+\pi^-$ decays, are required to originate from the interaction point (IP). We distinguish charged kaons from pions based on a kaon (pion) likelihood $\mathcal{L}_{K(\pi)}$ derived from the TOF, ACC and dE/dx measurements in the CDC. Photons are identified as isolated ECL clusters that are not matched to any charged track.

We identify B meson decays using the energy difference $\Delta E \equiv E_B^{\rm cms} - E_{\rm beam}^{\rm cms}$ and the beam-energy constrained mass $M_{\rm bc} \equiv \sqrt{(E_{\rm beam}^{\rm cms})^2 - (p_B^{\rm cms})^2}$, where $E_{\rm beam}^{\rm cms}$ is the beam energy in the cms, and $E_B^{\rm cms}$ and $p_B^{\rm cms}$ are the cms energy and momentum of the reconstructed B candidate, respectively. The signal candidates are selected by requiring 5.27 GeV$/c^2 <$ $M_{\rm bc} <$ 5.29 GeV$/c^2$ and a mode-dependent ΔE window. The dominant background for the $b \to s\overline{q}q$ signal comes from continuum events ($e^+e^- \to u\overline{u}, d\overline{d}, s\overline{s}, c\overline{c}$). We discriminate against this using event topology: continuum events tend to be jet-like in the cms, while $e^+e^- \to B\overline{B}$ events tend to be spherical. To quantify event topology, we calculate modified Fox-Wolfram moments and combine them into a Fisher discriminant [12]. We calculate a probability density function (PDF) for this discriminant and multiply it by a PDF for $\cos\theta_B$, where θ_B is the polar angle in the cms between the B direction and the beam axis. The PDFs for signal and continuum are obtained from Monte Carlo (MC) simulation and a data sideband, respectively. These PDFs are then used to calculate a signal [background] likelihood $\mathcal{L}_{\rm sig[bkg]}$, and we impose loose mode-dependent requirements on the likelihood ratio $\mathcal{R}_{\rm s/b} \equiv \mathcal{L}_{\rm sig}/(\mathcal{L}_{\rm sig} + \mathcal{L}_{\rm bkg})$. Figures 1.(a)-(l) show the reconstructed variables $M_{\rm bc}$, ΔE and $\mathcal{R}_{\rm s/b}$ after flavor tagging and vertex reconstruction (before vertex reconstruction for the decay $B^0 \to K_S^0\pi^0$); the corresponding signal yields are summarized in Table I.

TABLE I: Estimated signal yields $N_{\rm sig}$ in the signal region for each mode.

Mode	ξ_f	$N_{\rm sig}$
ωK_S^0	-1	118 ± 18
$f_0 K_S^0$	$+1$	377 ± 25
$K_S^0\pi^0$	-1	515 ± 32
$K^+K^-K_S^0$	$+0.86 \pm 0.18 \pm 0.09$	840 ± 34

We determine $\mathcal{S}_f$ and $\mathcal{A}_f$ for each mode by performing an unbinned maximum-likelihood fit to the observed Δt distribution. The decay rate is given by

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\Big\{1 + q\cdot\Big[\mathcal{S}_f \sin(\Delta m_d \Delta t) + \mathcal{A}_f \cos(\Delta m_d \Delta t)\Big]\Big\} \quad (2)$$

where τ_{B^0} is the B^0 lifetime and the b-flavor charge $q = +1(-1)$ when the tagging B meson is a B^0 ($\overline{B}^0$). The b-flavor of the accompanying B meson is identified by a tagging algorithm [13] that categorizes charged leptons, kaons and Λ's found in the event. The algorithm returns two parameters: the b-flavor charge q and r, which indicates the tag quality as determined from MC simulation and varies from $r = 0$ for no flavor discrimination to $r = 1$ for unambiguous flavor assignment. If $r \leq 0.1$, we set the wrong tag fraction to 0.5, and therefore the accompanying B meson provides no tagging information in this case. Events with $r > 0.1$ are sorted into six intervals.

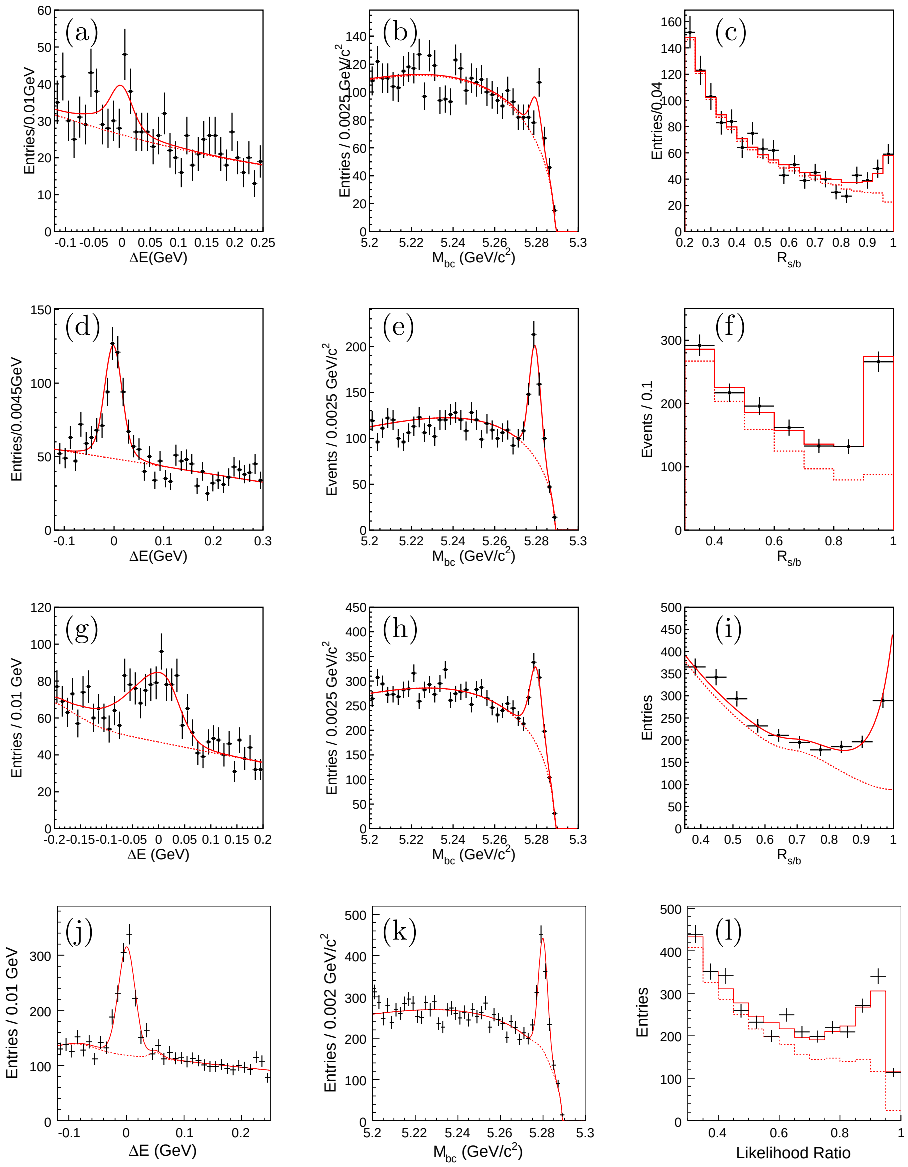

FIG. 1: ΔE, $M_{\rm bc}$ and $\mathcal{R}_{\rm s/b}$ distributions for (a, b, c) $B^0 \to \omega K_S^0$, (d, e, f) $B^0 \to f_0 K_S^0$, (g, h, i) $B^0 \to K_S^0\pi^0$ and (j, k, l) $B^0 \to K^+K^-K_S^0$. The solid curves show the fits to signal plus background distributions, and the dashed curves show the background contributions. To enhance the signal in the ΔE and $M_{\rm bc}$ projections, an additional cut on $\mathcal{R}_{\rm s/b}$ was applied (> 0.5).

To the PDF expected for the signal distribution (Eq. 2), the effect of incorrect flavor assignment is incorporated and then convolved with a resolution function $R_{\rm sig}(\Delta t)$ to take into account the finite vertex resolution. The wrong tag fractions for the six r intervals, w_l ($l = 1, 6$), and differences between B^0 and $\overline{B}{}^0$ decays, Δw_l, as well as the resolution parameters are determined using a high-statistics control sample of semileptonic and hadronic $b \to c$ decays.

We determine the following likelihood for each event:

$$\begin{aligned} P_i &= (1-f_{\rm ol})\int\Big[f_{\rm sig}\mathcal{P}_{\rm sig}(\Delta t')R_{\rm sig}(\Delta t_i-\Delta t') \\ &+ (1-f_{\rm sig})\mathcal{P}_{\rm bkg}(\Delta t')R_{\rm bkg}(\Delta t_i-\Delta t')\Big]d(\Delta t') \\ &+ f_{\rm ol}P_{\rm ol}(\Delta t_i). \end{aligned} \tag{3}$$

The signal probability $f_{\rm sig}$ depends on the r region and is calculated on an event-by-event basis as a function of $M_{\rm bc}$, ΔE and $\mathcal{R}_{\rm s/b}$ (and $M(\pi^+\pi^-\pi^0)$ for $B^0 \to \omega K_S^0$). For $B^0 \to f_0(980)K_S^0$, this fit yields the number of $B^0 \to \pi^+\pi^- K_S^0$ candidates that have $\pi^+\pi^-$ invariant mass within the $f_0(980)$ resonance region, which includes other contributions (e.g. $B^0 \to \rho^0 K_S^0$, $K^*\pi^\pm$ and non-resonant three-body decays) which peak like the signal in ΔE and $M_{\rm bc}$ distributions. To estimate these peaking backgrounds, we perform a fit to the $\pi^+\pi^-$ invariant mass distribution for the events inside the ΔE-$M_{\rm bc}$ signal region (Fig 2).

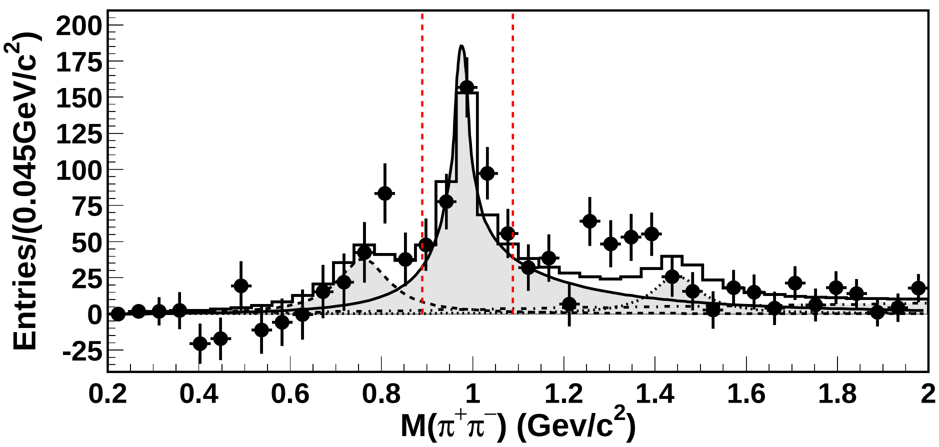

FIG. 2: $\pi^+\pi^-$ mass distribution for the f_0K_S events in the ΔE-$M_{\rm bc}$ signal box (shown here after background subtraction). The histogram is the result of the fit whereas the different contributions are shown (continuous line for $f_0(980)$, dashed for ρ^0 and dotted for f_X).

The PDF for background events, $\mathcal{P}_{\rm bkg}(\Delta t)$, is modeled as a sum of exponential and prompt components and is convolved with a sum of two Gaussians, $R_{\rm bkg}$. Parameters in $\mathcal{P}_{\rm bkg}(\Delta t)$ and $R_{\rm bkg}$ for background are determined from a fit to the Δt distribution for events in the ΔE-$M_{\rm bc}$ data sideband. $P_{\rm ol}(\Delta t)$ is a broad Gaussian function that represents an outlier component with a small fraction $f_{\rm ol}$. The only free parameters in the final fits are $\mathcal{S}_f$ and $\mathcal{A}_f$, which are determined by maximizing the likelihood function $L = \prod_i P_i(\Delta t_i; \mathcal{S}_f, \mathcal{A}_f)$ where the product is over all events.

Table II summarizes the fit results of $\sin 2\phi_1^{\rm eff}$ and $\mathcal{A}_f$. For the $B^0 \to K^+K^-K_S^0$ decay, the SM prediction is given by $\mathcal{S}_f = -(2f_+ - 1)\sin 2\phi_1^{\rm eff}$. The effective $\sin 2\phi_1$ value for this mode is found to be $+0.68 \pm 0.15 \pm 0.03^{+0.21}_{-0.13}$. The third error is an additional systematic error arising from the uncertainty of the $\xi_f = +1$ fraction. We define the raw asymmetry in each Δt bin by $(N_{q=+1} - N_{q=-1})/(N_{q=+1} + N_{q=-1})$, where $N_{q=+1(-1)}$ is the number of observed candidates with $q = +1(-1)$. Figure 3 shows this asymmetry for good tag quality ($r > 0.5$) events in each mode. The dominant sources of systematic error for $\mathcal{S}_f$ in $b \to s\bar{q}q$ modes are the uncertainties in the vertex reconstruction (0.01), in the background fraction (from 0.01 for $K_S\pi^0$ to 0.04 in ωK_S^0) and in the background Δt distribution (0.04 in $K_S\pi^0$

TABLE II: Results of the fits to the Δt distributions. The first error is statistical and the second error is systematic. The third error for $\sin 2\phi_1^{\rm eff}$ of $K^+K^-K_S^0$ is an additional systematic error arising from the uncertainty of the $\xi_f = +1$ fraction.

Mode	$\sin 2\phi_1^{\rm eff}$	$\mathcal{A}_f$
ωK_S^0	$+0.11 \pm 0.46 \pm 0.07$	$-0.09 \pm 0.29 \pm 0.06$
$f_0 K_S^0$	$+0.18 \pm 0.23 \pm 0.11$	$-0.15 \pm 0.15 \pm 0.07$
$K_S^0 \pi^0$	$+0.33 \pm 0.35 \pm 0.08$	$-0.05 \pm 0.14 \pm 0.05$
$K^+K^-K_S^0$	$+0.68 \pm 0.15 \pm 0.03^{+0.21}_{-0.13}$	$-0.09 \pm 0.10 \pm 0.05$

and 0.01 or less in others), and in the resolution function (0.05 for ωK_S and $K_S \pi^0$). The dominant sources for $\mathcal{A}_f$ are the effects of tag-side interference [14] (0.04), the uncertainties in the vertex reconstruction (0.02), in the background fraction (0.03 for $f_0 K_S^0$ and ωK_S^0 and < 0.02 for others). For the $f_0 K_S^0$ mode, additional systematics were included: uncertainties from the $M(\pi\pi)$ fit (0.06 for $\mathcal{S}_f$) and from the assumption on the CP content of the peaking background (0.08 for $\mathcal{S}_f$ and 0.04 for $\mathcal{A}_f$). For the $K_S^0 \pi^0$ mode, the uncertainty on the rare B component is taken into account (0.04 for $\mathcal{S}_f$ and 0.02 for $\mathcal{A}_f$). Other contributions come from uncertainties in wrong tag fractions, lifetime and mixing. A possible fit bias is examined by fitting a large number of MC events. We add each contribution in quadrature to obtain the total systematic uncertainty.

In summary, we have performed improved measurements of CP-violation parameters $\sin 2\phi_1^{eff}$ and $\mathcal{A}_f$ for $B^0 \to \omega K_S^0$, $f_0(980) K_S^0$, $K_S^0 \pi^0$ and $K^+K^-K_S^0$ using 535×10^6 $B\overline{B}$ events. Comparing the results for each individual $b \to s$ mode with those from the $B^0 \to J/\psi K^0$ decay, we have not observed a significant deviation with the present statistics.

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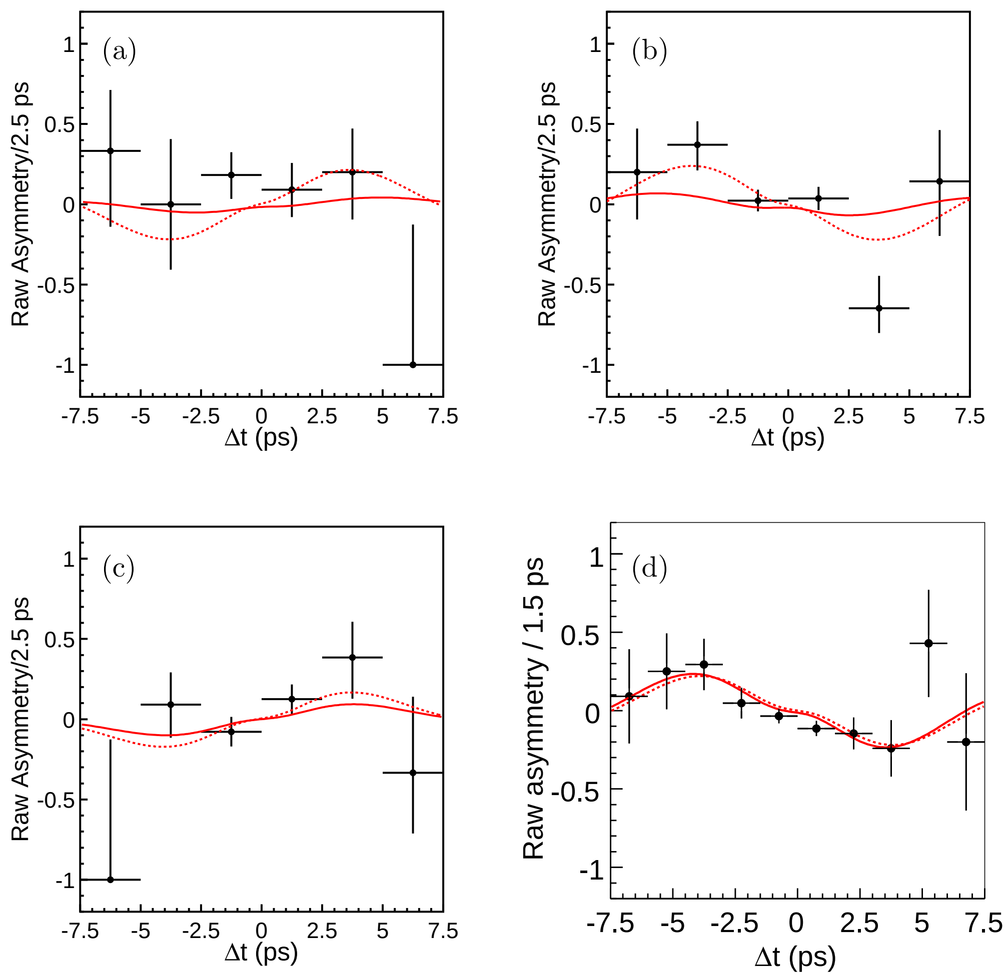

FIG. 3: Asymmetries of good-tagged events ($r > 0.5$) for (a) $B^0 \to \omega K_S^0$, (b) $B^0 \to f_0(980)K_S^0$, (c) $B^0 \to K_S^0\pi^0$ and (d) $B^0 \to K^+K^-K_S^0$. The solid curves show the results of the unbinned maximum-likelihood fits. The dashed curves show the SM expectation with the measurement of CP-violation parameters for the $B^0 \to J/\psi K^0$ mode ($\sin 2\phi_1 = +0.642$ and $\mathcal{A}_f = 0$)

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